The performance of improved H-modes at ASDEX Upgrade and projection to ITER

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Motivation: ITER performance

ITER: 15 MA, \( \langle n_e \rangle / n_{GW} = 0.85 \)

\[ P_{aux} = 40 \text{MW} \]

\[ P_{fus} \text{ (MW)} \]

\[ Q = 10, \quad P_{fus} \sim 400 \text{MW}. \]

Energy confinement:

IPB98\((y,2)\) scaling expression.

\[ \rightarrow \text{ITER size, 15MA/5.3T,} \]

\[ P_{aux} \leq 73 \text{ MW, } \langle n_e \rangle = 0.85, \ldots \]
Motivation: ITER performance

Integrated simulation codes: →
‘envelope’ of performance.

• Strong dependence,
of Q and $P_{\text{fus}}$ with $H_{98}(y,2)$.

Significant increase in ITER performance for ‘small’ increase in energy confinement.


George Sips 21st IAEA Fusion Energy Conference, Chengdu, China, 16-21 October 2006
Motivation: ITER performance

Integrated simulation codes: 'envelope' of performance.
- Strong dependence, of Q and $P_{\text{fus}}$ with $H_{98}(y,2)$.

Significant increase in ITER performance for 'small' increase in energy confinement.

$H_{98}(y,2) > 1$, and $\beta_N > 2$:
- Higher performance at 15 MA.
- Long pulse operation, $I_p=11$ to 14 MA, with $Q=5-10$ (Hybrid).
- DEMO: $H_{98}(y,2) \geq 1.2$, $\beta_N \geq 3.5$.
Motivation → Outline

• ASDEX Upgrade:
  Improved H-modes ($H_{98}(y,2) > 1$, and $\beta_N > 2$).

• Operational range:
  - wide range in density, $T_{i0}/T_{e0}$ and $\nu^*$.
  - at $q_{95} \rightarrow 3.1$.
  - high beta: Limits and control of NTMs.

• Scaling to ITER using experimental data.

• Conclusions.
H-mode operation for a wide range of plasma conditions:
• \( I_p = 0.6 - 1.4 \) MA, \( B_T = 1.6 - 3.0 \) T.

All type I ELMy H-modes:
• \( q_{95} < 5.5 \), stationary > 0.2 s.
  (values shown are averaged)
Current rise phase → Low magnetic shear

Current rise:
1. Early divertor configuration \( t \approx 0.5 \text{s} \).
2. → low \( \langle n_e \rangle \approx 3 \times 10^{19} \text{ m}^{-3} \), control of impurities.
3. Additional heating: Slow down the current penetration.

→ Low magnetic shear in the centre.
Low magnetic shear $\rightarrow$ Improved H-mode

- MSE data available in 2006. *McCarthy P. et al, EX/P3-7*
- Timing of preheating: ‘control’ of q-profile $\rightarrow H_{98}(y,2)$. *Stober J. et al, EX/P1-7*
- The q-profile remains flat in the core.
Low magnetic shear $\rightarrow$ Improved H-mode

- MSE data available in 2006.
- Timing of preheating: ‘control’ of q-profile $\rightarrow H_{98}(y,2)$.
- The q-profile remains flat in the core. MHD modes main candidate. Typically (3,2) NTMs and higher (m,n) activity or fishbone activity.
A second dataset includes all “improved H-mode” discharges:

- Early heating (some selected cases with late heating).
- Stationary for > 0.5 s.
- NOT just a selection of the best discharges.
Improved H-modes do not exclusively occupy the domain $H_{98}(y,2) > 1$ at $\beta_N = 2-3$.

Any H-mode, when it manages to achieve high beta is likely to develop low central shear in the centre, due to bootstrap current (overlap of ‘grey’ and ‘red’ data).

Physics criteria for improved H-modes would depend on the details of the current density profile (not routinely available).
ASDEX Upgrade: Improved H-mode data

<table>
<thead>
<tr>
<th>Average values</th>
<th>Type I ELMy H-modes (944)</th>
<th>Improved H-modes (259)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$q_{95}$</td>
<td>4.1</td>
<td>4.0</td>
</tr>
<tr>
<td>$H_{98}(y,2)$</td>
<td>1.08</td>
<td>1.21</td>
</tr>
<tr>
<td>$\beta_N$</td>
<td>1.89</td>
<td>2.43</td>
</tr>
<tr>
<td>$I_i$</td>
<td>0.95</td>
<td>0.89</td>
</tr>
</tbody>
</table>

Various physics studies on the reason for the high stability/confinement in improved H-modes.

**Core:** Stober J. et al, EX/P1-7

**Pedestal:** Suttrop W. et al, EX/8-5
Maggi C. et al, IT/P1-6
(various experiments)

Similar results have been obtained in other experiments (DIII-D, JET, JT-60U, NSTX..), for a range of conditions (See this conference !!).
Improved H-modes:
Typically operate at low density, $\langle n_e \rangle / n_{GW} = 0.35-0.6$.

After formation of $q(r)$, the density can be increased together with an increase in heating power and $\delta$.

$\langle n_e \rangle / n_{GW} = 0.85$, $H_{98}(y,2) \sim 1.2$ are obtained at high $\delta=0.4$.

→ At 1MA: $\langle n_e \rangle = 1.1 \times 10^{20}$ m\(^{-3}\).
→ Tolerable ELMs.
Operational range: $T_{i0}/T_{e0}$

1. Operation at high $<n_e>$.
2. ICRH and NBI at low $<n_e>$.

$\Rightarrow 0.7 < T_{i0}/T_{e0} < 2.5$

$T_{i0}/T_{e0} \sim 1$ for a substantial subset of the data, while maintaining high confinement.

Moreover, some of these discharges have low plasma rotation (low momentum input).
Operational range: $\nu^*$

Strongest correlation of maximum $H_{98}(y,2)$ with plasma collisionality ($\nu^*/\nu^*_\text{ITER}$).

Also density peaking ($n_{e0}/\langle n_e \rangle$) can be higher at lower $\nu^*/\nu^*_\text{ITER}$.

$\Rightarrow \beta$ and $\nu^*$ dependence of the IPB98(y,2) scaling expression are under investigation.

*Weisen H. et al, EX/8-4*

*McDonald D. et al, EX/P3-5*
Operational range: low $q_{95}=3.17$

1.2MA/2.0T $\Rightarrow q_{95} = 3.17$,
- NBI used with beta feedback, 50% of NBI is off-axis!
  Central ICRF heating.
- $<n_e>=6.4\times10^{19}\text{m}^{-3}$, $T_{i0}/T_{e0}=1.4$
  $<n_e>/n_{GW}=0.42$, $v^*/v_{ITER}^*=2$.
- $H_{98}(y,2)$ rises to 1.4 at $\beta_N=2.9$.
- $C_{W,\text{core}} = 2.5\times10^{-5}$ ($< 10^{-4}$).
Operational range: low $q_{95}=3.17$

1.2MA/2.0T $\rightarrow q_{95} = 3.17$,

- NBI used with beta feedback,
- 50% of NBI is off-axis.
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- $H_{98}(y,2)$ rises to 1.4 at $\beta_N=2.9$.
- $C_{W,\text{core}} = 2.5\times10^{-5}$ ($<10^{-4}$).

Core MHD:

\begin{align*}
(1,1) \text{ fishbones.} \\
(4,3) \text{ NTMs.} \\
\text{NO sawteeth.} \\
\text{Early (3,2) NTM when } \beta_N \sim 2.
\end{align*}
1. ECCD: Stabilise this (3,2) NTM at $q_{95} \approx 3.1$
After ECCD, discharge continues as improved H-mode (shown before).

Zohm H. et al, EX/4-1Rb

2. Otherwise (2,1) NTM may develop, and disruption recognition algorithms will act:
   (mode-lock, radiation peaking, regime identification, neural net):
   • React by issuing a soft stop or triggering killer gas injection.

Pautasso G. et al, EX/P8-7

3. Stabilisation of (3,2) NTM is **not required**
   for improved H-modes with $q_{95} > 4$.

Stober J. et al, EX/P1-7
Scaling to ITER using experimental data

Motivation:

• Integrated simulation codes rely on use of transport models and models for actuators, require benchmarking on current experiments.

• **Scaling the measured kinetic profiles to ITER**: 100% fit to experimental data, gradient length preserved, pedestal.
  
  ➢ Use experimental profile shapes.
  ➢ Same $\beta_N$, H-factor's.
  ➢ Use ITER geometry.
  ➢ Impurities: Be 2 %, Ar 0.12 %, He 4.3 % $\rightarrow (n_D+n_T)/n_e \sim 0.8$.

  *Luce T. et al 2004 Phys. Plasmas 11 2627*

Assemble set of discharges with good profile measurements.

ITER predictions: $P_{fus}$, $P_{aux}$, Q (+ other parameters using ASTRA).

*Tardini G. et al 33rd EPS Conference, Rome 19-23 June 2006, P1.112*
Density: Use shape of $n_e$ profile from ASDEX Upgrade, set $<n_e> = 0.85n_{GW}$.

Temperatures: Use shape of $T_i$ profile or use shape of $T_e$ profile from ASDEX Upgrade (select highest), set $T_i = T_e$ and $\beta_N^{ITER} = \beta_N^{AUG}$. 
Density: Use shape of $n_e$ profile from ASDEX Upgrade, set $\langle n_e \rangle = 0.85n_{GW}$.

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Scaling to ITER: $q_{95}=3.0$, $\beta_N=2.1$, high $<n_e>$

Comparison with integrated ITER scenario modelling (Scenario 2):

- **Density:** Assumed flat.
- **Temperatures:** Set pedestal, models for core transport & heating systems.
Scaling to ITER: $q_{95}=3.17$, $\beta_N=2.9$

At higher $\beta_N$ (Improved H-mode):
- Temperature profiles rise over whole plasma region.
- Consistent with observations of increased edge pedestal.

Suttrop W. et al, EX/8-5
Maggi C. et al, IT/P1-6
Prediction of fusion performance in ITER

**ITER predictions at $<n>/n_{GW}=0.85$**

4 typical cases:

<table>
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<tr>
<th>$q_{95}$</th>
<th>$\beta_N$</th>
<th>$H_{98}(y,2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.05</td>
<td>2.10</td>
<td>0.95</td>
</tr>
<tr>
<td>3.17</td>
<td>2.87</td>
<td>1.40</td>
</tr>
<tr>
<td>3.8</td>
<td>2.63</td>
<td>1.32</td>
</tr>
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<td>4.6</td>
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<td>1.44</td>
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</table>

$P_{aux} > 73$ MW$^*$

Open symbols $P_{aux} > 73$ MW$^*$

Closed symbols $P_{aux} \leq 73$ MW$^*$

* $P_{aux}$ based on using IPB98($y$,2) scaling.
Operation at $\beta_{N,th}=2-3$:

- Significant fusion power for $I_p=9.5\text{MA}$ to $I_p=12\text{MA}$. With bootstrap current fraction $f_{BS}\sim0.4$, and $Q=6-15$.
  Long pulse lengths ($>400\text{s}$).

- At low $q_{95}\sim3$ ($I_p=14-15\text{MA}$) would in principle be able to reach $P_{\text{ fus}}\sim1\text{GW}$, $Q=\infty$.

* $P_{\text{aux}}$ based on using IPB98(y,2) scaling.
Prediction of fusion performance in ITER

ITER Physics Basis 1999
Nucl. Fusion 39 2137

Petty G. et al 2003
Fusion Sci. Technol. 43 1

Cordey J. G. et al 2005
Nucl. Fusion 45 1078

Q and input power ($P_{aux}$) required (ASDEX Upgrade profile data):

- Calculated for three different energy confinement scaling expressions.
- Using IPB98(y,2): In some high $\beta$ cases: $P_{aux} > 73$MW.
  $I_p < 11$MA, despite $H_{98}(y,2)$~1.4.
Conclusions

**ASDEX Upgrade:**
H-modes with *low magnetic shear in the centre*: \( H_{98}(y,2) > 1 \) and \( \beta_N = 2-3.5 \).

- Operation at high density and \( T_{i0}/T_{e0} \sim 1 \) is demonstrated.
- Highest \( H_{98}(y,2) \) values are achieved at ITER relevant \( \nu^* \).
- At \( q_{95} = 3.1 \): \( H_{98}(y,2) = 1.4 \), \( \beta_N = 2.9 \), fishbone activity keeps \( q(r) \) stationary.
- ECCD can be used to stabilise (3,2) NTM activity (\( q_{95} \sim 3 \)).

**ITER predictions**, scaling kinetic profile shapes: \( \langle n_e \rangle = 0.85 n_{GW} \), keep \( \beta_{N,th} \).

At \( q_{95} = 3.1 \): \( P_{\text{fus}} = 1070 \text{ MW}, Q = \infty \).

At \( I_p = 9.5-12\text{MA} \): \( P_{\text{fus}} \) 300-600 MW, \( Q = 6-15 \) (some cases \( P_{\text{aux}} > 73 \text{ MW} \)).
Back-up slides
Operation: Tungsten coverage → 85%

All H-modes require central ICRH or ECRH to avoid impurity accumulation. Operation at $<n_e> \sim 4-6 \times 10^{19} \text{ m}^{-3}$ requires a boronisation to minimise tungsten influxes.

Gruber O. et al, OV/2-3
Dux R. et al, EX/3-3Ra
Operational range: Density, $v^*$

Strongest correlation of maximum $H_{98}(y,2)$ with plasma collisionality ($v^*/v^*_\text{ITER}$).

Also density peaking ($n_{e0}/\langle n_e \rangle$) can be higher at lower $v^*/v^*_\text{ITER}$.

$\rightarrow \beta$ and $v^*$ dependence of the IPB98(y,2) scaling expression are under investigation.

*McDonald D. et al, EX/P3-5*
Operational range: low $q_{95}=3.17$

Core MHD activity

- $F$ (kHz)
- ELMs
- Soft X-ray data
- (4,3) NTMs
- Fishbone activity

Operational range: low $q_{95}=3.17$
Use of ECCD to stabilise (3,2) NTM

**Graphs and Data:***
- **# 21269 (1MW ECRH)**
- **# 21272**
- **$n_e$ (x10^{19} m^{-3})**
- **$T_e$ (keV)**
- **$H_{98}$ (y,2)**
- **$\beta_N$**
- **$P_{ECRH}$ (MW)**

**Key Points:**
- Use of ECCD to stabilise (3,2) NTM.
- Graphs showing $3,2$ activity.
- Killer gas disruption.
- ECRH deposition.

**References:**
- Zohm H. et al, EX/4-1Rb
ITER Scenario 2

ITER Physics Basis 1999 Nucl. Fusion 39 2137

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<th>(&lt;n_e&gt;/n_{GW}) = 0.85</th>
<th>(q_{95})</th>
<th>(I_p) (MA)</th>
<th>(\beta_N)</th>
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<th>(H_{98}(y,2))</th>
<th>(Q)</th>
<th>(P_{aux}) (MW)</th>
<th>(\langle n_e \rangle) (10^{19} m^{-3})</th>
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<td>3.0</td>
<td>15.0</td>
<td>1.8</td>
<td>400</td>
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Scaling to ITER: $q_{95}=3.0$, $\beta_N=2.1$, high $<n_e>$

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<th>$H_{98}(\gamma,2)$</th>
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<th>$P_{aux}$ (MW)</th>
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<td>AUG #17847</td>
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<td>619</td>
<td>0.95</td>
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<td>(78)</td>
<td>9.9</td>
<td>11.2</td>
<td>20.3</td>
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$\beta_{N,th}^{ITER} = \beta_{N,th}^{AUG}$

$T_i = T_e$
Scaling to ITER: $q_{95}=3.17$, $\beta_N=2.9$

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<td>AUG #20449</td>
<td>3.17</td>
<td>14.2</td>
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<td>1.40</td>
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<td>0</td>
<td>9.6</td>
<td>12.2</td>
<td>29.5</td>
</tr>
</tbody>
</table>
Scaling to ITER: $q_{95}=3.8$, $\beta_N=2.6$

![Graph showing $n_e$ and $T_{i,e}$ profiles for different scenarios.]

<table>
<thead>
<tr>
<th>$&lt;n_e&gt;/n_{GW}$</th>
<th>$q_{95}$</th>
<th>$I_p$ (MA)</th>
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<tr>
<td>AUSG #17870</td>
<td>3.8</td>
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<td>11.4</td>
<td>52</td>
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$\beta_{N,th}^{ITER} = \beta_{N,th}^{AUG}$

$T_i = T_e$
Scaling to ITER: $q_{95}=4.6$, $\beta_N=2.4$

<table>
<thead>
<tr>
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<th>$&lt;n_e&gt;/n_{GW}$</th>
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<td>AUG #20448</td>
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<td>2.41</td>
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$\beta_{N,\text{th}}^{\text{ITER}} = \beta_{N,\text{th}}^{\text{AUG}}$

$T_i = T_e$
### Prediction of fusion performance in ITER

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*Profile shapes*
Prediction of fusion performance in ITER

Calculated bootstrap fraction \( f_{BS} \) increases at lower current.

ITER (15MA) \( \sim 0.18 \).

Maximum of cases presented here: \( f_{BS} \sim 0.4 \).

A current ramp to lower plasma currents compared to reference design AND the ability to operate at same stored energy.

\( \rightarrow \) longer pulse length.
Most of the scaled edge pedestal temperatures are within range of what is expected for typical H-modes in ITER.

5.3 keV ± 23%